Transdisciplinary Engineering: A Paradigm Shift
C. Chen et al. (Eds.)

doi:10.3233/978-1-61499-779-5-829

Toward Resilient Vessel Traffic Service: A Sociotechnical Perspective

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Abstract. Vessel Traffic System (VTS) is a typical complex sociotechnical system that provides various supporting services for vessels. With the booming of maritime transportation, VTS becomes more and more important in promoting traffic fluency, efficiency, and safety in designated geographical areas. However, the performance of VTS is frequently threatened by external and internal incidents, which leaves the maritime traffic in a dangerous situation. Therefore, VTS must be resilient to cope with these disturbances and maintain an acceptable service level. Focusing on this problem, this paper first analyses the architecture of VTS from the perspective of sociotechnical systems. Thereafter, the definition of resilient VTS is introduced. Through interaction network analysis, the key contributing factors for resilient VTS are identified. Finally, based on the results, several guidelines for realizing resilient VTS are proposed.

Keywords. Vessel Traffic Service (VTS), Resilience Engineering, Sociotechnical Systems, Systems Engineering, Human-Machine Systems.

Introduction

Vessel Traffic Service (VTS) refers to the integrated shore-side system that provides various navigational support for vessels and extensive traffic management within a port or waterway. It is a typical sociotechnical system that requires seamlessly cooperation among organizations, humans, and various information systems [1]. VTS is usually implemented by a competent authority to guarantee the safety and improve the efficiency of vessel traffic, as well as protecting the environment in its area [2]. With the booming of maritime transportation, especially the continuous and rapid growth in the number, size, and cargo volumes of merchant vessels, the importance of VTS has been widely recognized for promoting traffic fluency and safety in designated geographical areas [3]. Extensive research and practices have also been made to improve the service level of VTS from various aspects, including the technical aspect [4, 5], managerial and operational aspect [6, 7], and organizational aspect [8]. However, in the current practices, the performance of VTS is frequently threatened by various external and internal incidents, such as the sudden increase of traffic or cargo volumes, traffic accidents, changes of organizational regulations, fatigues of operators and pilots, and even technical failure of information systems, leaving the maritime traffic in risks. Therefore, VTS must be resilient to cope with these disturbances to maintain an

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acceptable service level, and finally ensure a safe, smooth, and efficient traffic environment within its area of responsibility.

The concept of resilience was initially introduced in ecological system to describe its ability to adapt the condition changes and keep a balanced situation from disruptions [9]. Recently, the importance of resilience has been broadly recognized in diverse areas, such as disaster management [10], transportation system [11], service system [12], and supply chain management [13]. Extensive methods have also been proposed to improve their resilience, such as optimizing network structure (e.g. in transportation systems [14] and supply chain management [15]), providing redundant or backup resources [16], and using "stronger" components [17]. Research has also been conducted on understanding and improving the resilience of sociotechnical systems. For instance, Ruault, et al. [18] studied the relationships between the resilience of sociotechnical systems and systems engineering and architecture, and identified the key influencing factors that should be considered for improving the resilience. Guarino, et al. [19] identified the importance of transparency in realizing resilient sociotechnical system, and presented the necessity of ontology-driven sociotechnical systems. In addition, Duff, et al. [20] proposed a multi-level model to diagnose and measure the team resilience in sociotechnical systems. In VTS, there are also some efforts have been done. Through modelling the daily operations in three VTSs, Praetorius, et al. [21] identified the key functions that need to be improved to realize safe, efficient, and resilient VTS. Besides, taking the arrival part of a mission as an example, Praetorius, et al. [22] compared VTS with Air Traffic Control (ATC) from the aspect of resilience engineering, and presented recommendations to deal with the complex operations for both of them.

Although these works have brought great moves toward resilient VTS, the research is still limited and incomplete. Specifically, research is still needed on identifying the key contributing factors for resilient VTS, and methods for improving its resilience. Due to the complexity of VTS and its safety-critical nature, it is also challenging to directly apply the existing knowledge accumulated in resilience engineering from other domains.

Taking these into consideration, this research is conducted from the perspective of sociotechnical systems to unfold the myths of resilient VTS. More specifically, four questions are to be answered in this research: (1) How to understand VTS as a sociotechnical system? (2) What is resilient VTS? (3) What are the key contributing factors for resilient VTS? And (4) how to improve the resilience of VTS.

The rest of this paper is organized as follows. Section 1 makes a thorough analysis of VTS from the perspective of sociotechnical system. Section 2 identifies the system disturbances in VTS and introduces the definition of resilient VTS. In Section 3, the key contributing factors for resilient VTS is figured out through interaction network analysis and Section 4 gives the guidelines for effectively improving the resilience of VTS. Finally, Section 5 concludes the whole paper and points out the future works.

1. VTS – A Complex Sociotechnical System

The delivery of VTS services is a group activity that requires extensive and intensive cooperation among various parties, from organizations, humans, to various information systems. According to the classification of complex systems [23], VTS can be treated as a typical complex sociotechnical system. The overall architecture of VTS can be depicted as shown in Figure 1. The key components involved are derived from extensive review on VTS standards, systems, and literatures, as well as unstructured interviews with watch managers in Singapore. Following the sociotechnical theory [24], all these components are categorized into four parts: environment, information system, organization, and human.

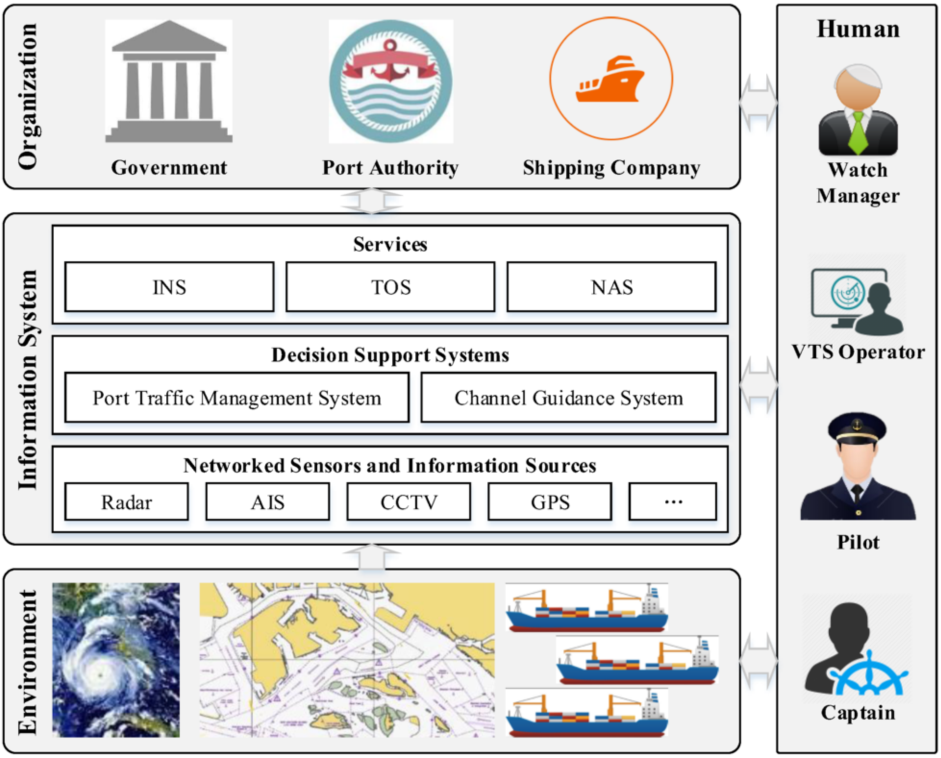

Figure 1. Overall Architecture of VTS.

Environment part refers to the targeted external maritime environment in the area of responsibility. The environmental information that would be monitored in VTS includes the meteorological and hydrological conditions, port and strait traffic information, and real-time status of vessels.

Information system part can be treated as the technology part in sociotechnical system. It contains all the technologies adopted, which is responsible for monitoring the real-time environmental conditions and providing decision support for managing the vessel traffic. Basically, this part contains three layers, they are Networked Sensors and Information Sources (NSIS) layer, Decision Support Systems (DSSs) layer, and Services layer. NSIS layer contains various sensors and systems that are responsible for collecting various real-time data from the environment. Typical sensors and systems involved include radar, AIS (Automatic Identification System), CCTV (Closed Circuit Television), GPS (Global Positioning System), etc. Based on the real-time information collected by NSIS layer, various DSSs are built, like Port Traffic Management System (PTMS) and Channel Guidance System (CGS), to support the decision-making processes in VTS. Services layer contains the services provided by the DSSs. It also serves as the interfaces between humans and information systems. According to the specifications given by IMO (International Maritime Organization) [2], these services include Information Service (INS), Traffic Organization Service (TOS), and Navigational Assistance Service (NAS). INS provides environmental information and other transit influencing factors to all the participated vessels through broadcasting. TOS aims at preventing congestions and other dangerous situations in VTS area. It mainly focuses on the operational management of traffic through VHF broadcasts. NAS provides navigation support for vessels in difficult and extreme circumstances. It is usually provided upon request of a vessel.

The organization part includes government, port authority, and shipping company. Government is responsible for enacting the regulations and rules for VTS, while port authority is responsible for implementing VTS in its area of responsibility. For the shipping companies, they should follow the regulations provided by government and port authority to manage related vessels, and update necessary shipping information to the port authority.

Humans are the key to deliver the services provided by information system, satisfy the goals of organization, and control the vessel traffic environment actively. Basically, humans can be divided into four roles. Watch managers are the decision makers in all these organizations. They are in charge of the working schedules of VTS operators, the assignment of pilots, and the voyage or passage plan of vessels. They also serve as the bridge between the other three roles and the organizations. VTS Operator is responsible for monitoring and coordinating the movement of all the vessels in VTS areas based on the services provided by information system. Pilot here refers to the professional staff of the port that provides navigational support on broad for the incoming vessels. They will get on the pre-assigned vessels at the designated place to help them on sailing in the port area and berthing at the port. Captain (Master) is the person who is in charge of a vessel.

2. Resilient VTS

During the execution of VTS, all its four parts would encounter various disturbances that decrease the service level of VTS, thus expose the maritime traffic in a dangerous situation. Through field observation and unstructured interview with watch managers and VTS operators, the typical system disturbances in VTS can be listed in Table 1.

In general, these disturbances would affect the VTS from two aspects. On the one hand, they would decrease the capability and performance of service supply from VTS, such as prolonged response time, decreased accuracy, increased error rate, and missed actions. On the other hand, these disturbances would also increase the demands for VTS services. For example, when facing bad weather or traffic congestions, relative more vessels will need to be served, and the workload of VTS will increase accordingly.

Once the service supply of VTS cannot satisfy the demands for services due to these disturbances, the imbalanced situation is occurred and the VTS area would be in danger. Aiming at dealing with such situations and ensuring a safe maritime traffic environment, resilient VTS is thus introduced. More specifically, the resilience of VTS refers to the ability of VTS to recover from an imbalanced situation to a safe situation, where its service supply can meet the demands of services.

Based on this definition, the resilience of VTS can be measured from three axioms: 1) Time: The recovering time from imbalanced situation to the safe situation; 2) Extent:

The recovered extent of VTS; 3) Cost: The cost for recovering from imbalanced situation to the safe situation.

Table 1. System Disturbances in VTS.

Parts	Typical Disturbances
Environment	Bad weather; Change of hydrological conditions; Maritime accidents; Traffic congestions; Sudden increase of maritime traffic or cargo volumes; Decreased manoeuvrability of vessels.
Information System	Interruption of power supply; Break down of operation console; Technical failure of DSSs; Damage to information infrustracture; Disconnection of networks.
Organization	Changes of organizational regulations or management objectives; Job rotation; Work shift.
Human	Human fatigues; Communication Failure; Operational errors; Absence of VTS operators; Delay of actions.

3. Influencing Factors for Resilient VTS

In order to improve the resilience of VTS, it is a prerequisite to identify the influencing factors for resilient VTS. As a typical complex sociotechnical system, the factors are also diverse and complex [18, 21, 25]. Besides the resilience of all the involved system components, the interactions among them will also contribute to the resilience of VTS. However, in practices, due to the limited budget and labour forces, it is impossible to enhance all of them for resilient VTS. Therefore, it is urgently needed to identify the key influencing factors, and then make targeted enhancement for effectively improving the resilience of VTS.

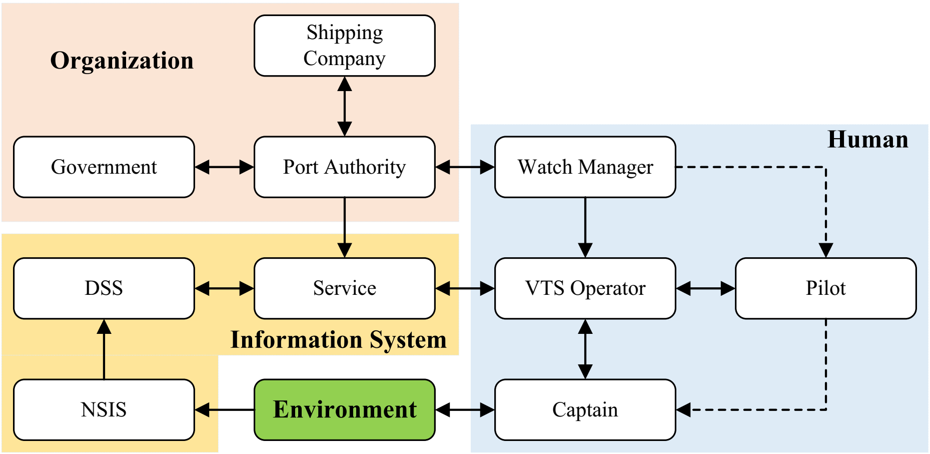

Figure 2. Interaction Network in VTS.

Based on the VTS architecture discussed in Section 1, through field observations at one VTS centre in Singapore, and unstructured interviews with VTS operators and port mangers, the interactions among the system components in VTS have been identified and illustrated as a directed graph, as shown in Figure 2. The blocks (nodes) refer to the key components in information systems, organizations, and humans, while the arrows (edges) stand for the interactions among these components. The arrow with dotted line means the interaction is out of the control scope of VTS.

Many methods are available for measuring the importance of nodes in networks [26]. Considering the context of VTS, the idea of local centrality is adopted, which considers not only the degree of node itself, but also the degrees of its nearest neighbours. Besides, since the out-degree of a component means it has the power to affect the others, it should have higher importance compared with the in-degree. Furthermore, since environment represents the management target of the whole VTS, it should have higher importance compared with the others. In addition, the shortest distance between the evaluating node to the environment node should also be considered in the importance measurement.

Let α represents the weight of out-degree of a node, e_{ij}^{out} represents the weight of jth out-degree of node i, while β and e_{ij}^{in} represent these of in-degree, the degree of node i can be calculated as follows:

$$d_i = \alpha \sum e_{ij}^{out} + \beta \sum e_{ij}^{in}$$

The importance of component i can be measured as follows:

$$\mathrm{K}(i) = \gamma_i d_i + \sum_{j \in N_i} \gamma_j d_j - l_i$$

Where γ_i refers to the weight of node i, N_i is the set of the nearest neighbours of node i, and l_i is the shortest distance between node i to the environment node.

Through consulting with VTS expert and without loss of generality, all the weights involved are assigned with 1 (normal) or 2 (important). More specifically, except the environment node (γ_0=2), all the weights of the other nodes are set as 1. For the edges, the edge with dotted line is assigned with 1 and the others are assigned with 2. Finally, to differentiate the out-degree and in-degree, α is set with 2 while β is 1.

Based on the equations and parameter settings given above, the importance of every component in Figure 2 can be evaluated. Start from the most important one, the components and their importance values are listed as follows: VTS Operator (64), Service (61), Captain (59), Watch Manager (58), Port Authority (56), Pilot (50), NSIS (33), Government (29), Shipping Company (29), and DSS (26). From the results, VTS Operator is the most important influencing factors for realizing resilient VTS, followed by Service and Captain. DSS has been identified as the least important factor, which is consistent with the result found in ATC [27].

4. Guidelines for Improving the Resilience

Based on the above analysis, several guidelines can be given to realize resilient VTS.

Firstly, in order to effectively improve the resilience of VTS with limited resources, relatively much more efforts should be paid on VTS operators, services (INS, TOS, and NAS), and captains.

Secondly, the interactions among the three most important factors should also be enhanced to improve the resilience of VTS. Efforts can be made from two aspects: (1) Considering the interactions between services and VTS operators, Human-Computer Interface (HCI) should be improved to enhance situational awareness of VTS operators, which has also been identified as a key to realize operational resiliency in VTS [21]. (2)

For the interactions between VTS operators and captains, the communication channel should be diversified and robust to cope with disturbances, and standard terminology is also recommended to facilitate the communications between them.

Thirdly, among the three most important influencing factors, VTS operators serve as the bridge between the other two factors. The resilience of VTS operator is thus vital for realizing resilient VTS. Aiming at improving the capabilities of VTS operators on dealing with the disturbances, effective training of them, rational job rotations to decrease their fatigues, and sufficient backup operators should be considered. Besides, the cooperation among operators should also be improved through standard communication channels and unified terminologies and marks.

5. Conclusions

In order to unfold the myths of resilient VTS and provide effective recommendations to improve the resilience of VTS, this research has made a thorough analysis of VTS from the perspective of sociotechnical systems. Firstly, based on the sociotechnical theory, the architecture of VTS, as well as the interactions among its components, has been analysed. Besides, the system disturbances of VTS have also been identified. Secondly, in accordance with the research in service systems, the definition of resilient VTS has been proposed with three measurement axioms. Thirdly, through interaction network analysis, the key influencing factors for resilient VTS have been identified, which are VTS Operator, Service, and Captain. Fourthly, several guidelines for improving the resilience of VTS have been proposed.

This research can be further extended from three aspects. First, more investigations should be made to make a deeper analysis on the VTS interaction network, and adjust the parameters for evaluating the importance of influencing factors. Second, efforts can be paid on building the quantitative model for measuring the resilience of VTS. Third, focusing on every aspect of VTS, research can be conducted on the effective methods for improving its resilience.

Acknowledgement

This research is supported by Singapore Maritime Institute research project (SMI-2014-MA-06).

References

[1] G. Praetorius and E. Hollnagel, Control and resilience within the maritime traffic management domain, *Journal of Cognitive Engineering and Decision Making,* Vol. 8, 2014, pp. 303-317.
[2] IMO, *IMO Guidelines for Vessel Traffic Services*, ed: International Maritime Organization, 1997.
[3] G. Praetorius, *Vessel Traffic Service (VTS): a maritime information service or traffic control system? Understanding everyday performance and resilience in a socio-technical system under change*, doctoral thesis, Chalmers University of Technology, 2014.
[4] N. Park and H. C. Bang, Mobile middleware platform for secure vessel traffic system in IoT service environment, *Security and Communication Networks,* Vol. 9, 2014, pp. 500-512.
[5] D. S. Misović, S. D. Milić, and Ž. M. Đurović, Vessel Detection Algorithm Used in a Laser Monitoring System of the Lock Gate Zone, *IEEE Transactions on Intelligent Transportation Systems,* Vol. 17, 2016, pp. 430-440.

[6] A. Brodje, M. Lundh, J. Jenvald and J. Dahlman, Exploring non-technical miscommunication in vessel traffic service operation, *Cognition, technology & work,* Vol. 15, 2013, pp. 347-357.

[7] J. T. Mansson, M. Lutzhoft and B. Brooks, Joint Activity in the Maritime Traffic System: Perceptions of Ship Masters, Maritime Pilots, Tug Masters, and Vessel Traffic Service Operators, *The Journal of Navigation,* 2016, pp. 1-14.

[8] F. van Westrenen and G. Praetorius, Maritime traffic management: a need for central coordination?, *Cognition, technology & work,* Vol. 16, 2014, pp. 59-70.

[9] C. S. Holling, Resilience and stability of ecological systems, *Annual review of ecology and systematics,* Vol. 4, 1973, pp. 1-23.

[10] G. Xu. Cloud Asset Management for Urban Flood Control. Ph.D Thesis, The University of Hong Kong, 2016.

[11] R. Faturechi and E. Miller-Hooks, Travel time resilience of roadway networks under disaster, *Transportation research part B: methodological,* Vol. 70, 2014, pp. 47-64.

[12] J. Wang, Towards a resilient networked service system, PhD thesis, University of Saskatchewan, 2013.

[13] J. Wang, R. R. Muddada, H. Wang, J. Ding, Y. Lin, C. Liu, *et al.*, Toward a resilient holistic supply chain network system: Concept, review and future direction, *IEEE Systems Journal,* Vol. 10, 2016, pp. 410-421.

[14] W. Ip and D. Wang, Resilience and friability of transportation networks: evaluation, analysis and optimization, *IEEE Systems Journal,* Vol. 5, 2011, pp. 189-198.

[15] Y. Kristianto, A. Gunasekaran, P. Helo, and Y. Hao, A model of resilient supply chain network design: A two-stage programming with fuzzy shortest path, *Expert systems with applications,* Vol. 41, 2014, pp. 39-49.

[16] T. Sakano, Z. M. Fadlullah, T. Ngo, H. Nishiyama, M. Nakazawa, F. Adachi, *et al.*, Disaster-resilient networking: a new vision based on movable and deployable resource units, *IEEE Network,* Vol. 27, 2013, pp. 40-46.

[17] M. Panteli and P. Mancarella, The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience, *IEEE Power and Energy Magazine,* Vol. 13, 2015, pp. 58-66.

[18] J. R. Ruault, F. Vanderhaegen, and D. Luzeaux, Sociotechnical systems resilience, in *INCOSE International Symposium*, 2012, pp. 339-354.

[19] N. Guarino, E. Bottazzi, R. Ferrario, and G. Sartor, Open ontology-driven sociotechnical systems: Transparency as a key for business resiliency, in *Information systems: crossroads for organization, management, accounting and engineering*, ed: Springer, 2012, pp. 535-542.

[20] S. Duff, K. Del Guidice, J. Flint, N. Nguyen, and B. Kudrick, The diagnosis and measurement of team resilience in sociotechnical systems, in *Resilient Control Systems (ISRCS), 2014 7th International Symposium on*, 2014, pp. 1-5.

[21] G. Praetorius, E. Hollnagel, and J. Dahlman, Modelling Vessel Traffic Service to understand resilience in everyday operations, *Reliability engineering & system safety,* Vol. 141, 2015, pp. 10-21.

[22] G. Praetorius, F. van Westrenen, D. Mitchell, and E. Hollnagel, Learning lessons in resilient traffic management: a cross-domain study of vessel traffic service and air traffic control, in *HFES Europe Chapter Conference: Human factors: a view from an integrative perspective. Proceedings Toulouse*, 2012.

[23] R. R. Hoffman, D. O. Norman, and J. Vagners, Complex Sociotechnical Joint Cognitive Work Systems?, *IEEE Intelligent Systems,* Vol. 24, 2009.

[24] M. C. Davis, R. Challenger, D. N. Jayewardene, and C. W. Clegg, Advancing socio-technical systems thinking: A call for bravery, *Applied ergonomics,* Vol. 45, 2014, pp. 171-180.

[25] S. K. Yenson, S. Phillips, A. Davis, and J. Won, Exploring human-system resiliency in air traffic management technologies, in *Digital Avionics Systems Conference (DASC), 2015 IEEE/AIAA 34th*, 2015, pp. 3D2-1-3D2-10.

[26] L. Jian-Guo, R. Zhuo-Ming, G. Qiang, and W. Bing-Hong, Node importance ranking of complex networks, Acta Physica Sinica, Vol. 62, 2013, No. 17, doi:10.7498/aps.62.178901.

[27] F. Trapsilawati, X. Qu, C. D. Wickens, and C.-H. Chen, Human factors assessment of conflict resolution aid reliability and time pressure in future air traffic control, *Ergonomics,* Vol. 58, 2015, pp. 897-908.